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THE REDISTRIBUTION OF STRESSES AROUND LONGWALL EXTRACTION PANELS IN BEDDED ROCK MASSES

Ross Seedsman¹

ABSTRACT: Longwall mining is conducted in bedded rock masses which are not only inhomogeneous but also transversely isotropic. Assuming isotropic rock mass properties can substantially under-estimate the impact longwall extraction can have on the redistribution of horizontal stresses. By invoking the transverse isotropic parameters derived from data on stress-relief roadways it is demonstrated that stress modifications can extend laterally 8 to 10 times the effective excavation height. For longwalls this may mean stress changes could extend up to a 1 km distance. Recognition of the role of transverse isotropy has implications to the understanding of stress concentration effects at the maingate/face corner and also predicting mining conditions in new longwall districts.

INTRODUCTION

In geotechnical engineering the term isotropy refers to a condition whereby the properties are the same in all directions. This differs from the concept of homogeneity which refers to the presence of the same material – the layering of different rock types often seen in numerical models recognises inhomogeneity but not transverse isotropy. Sedimentary rock masses are characterised by the presence of laterally continuous bedding discontinuities at spacings ranging from millimetres to tens of metres and must be considered to be transversely isotropic at all scales. Transverse isotropy in an equivalent continuum invokes the same elastic properties in one plane and a different set of properties out-of-plane and hence can be an analogue to bedding in sedimentary rock masses. Despite this it is common practice to model such rock masses as being isotropic both in terms of their deformation properties and their strength. Seedsman (2011) highlighted the possible role of transverse isotropy in modifying the stress redistribution about coal mine roadways and evidence from coal mines and tunnels was interpreted to propose that a Young's Modulus/Independent shear modulus (E/G) ratio of 100 could be applied to sedimentary rock masses with bedding spacings in the order of 200 mm.

Recently Gale (2013) and Galvin (2016) have published analyses of stress distributions around longwall panels using the isotropic assumption and both authors determined distortions to the pre-mining stress field extending out only about 30 m from a longwall face. Recent observations of ground conditions in two longwall mines at depths of 300 m and 550 m have suggested that longwall extraction can modify the horizontal stress field to distances in excess of 500 m. This paper examines how the transverse anisotropy parameter proposed for the roadway scale can also be applied to the scale of a longwall extraction goaf.

LITERATURE REVIEW

Based on stress monitoring in a mine at 500 m depth Gale and Mathews (1992) proposed reductions in horizontal stress could be achieved up to 40 m distance from a roadway that had damaged ("softened") zones extending 4.5 m to 5 m into both the roof and floor. Seedsman (2017) used their case study data to determine that an E/G ratio of 100 could be used for interbedded laminates and sandstones. Compared to the isotropic case the use of this E/G parameter extended the distance for stress relief from 15 m to 60 m (stress ratio reduced from 1.6 to 1.4 in Figure 1). This represents a distance/excavation height aspect ratio of 60/8 or 7.5, which if applied to a longwall void defined by combined caved and fractured zones of 100 m would imply stress changes at 750 m distance. In regard to the vertical stress there are significant differences close to the excavation which may be a numerical limitation, but the width of vertical stress abutment is similar at about 20 m for the isotropic and transversely isotropic cases.

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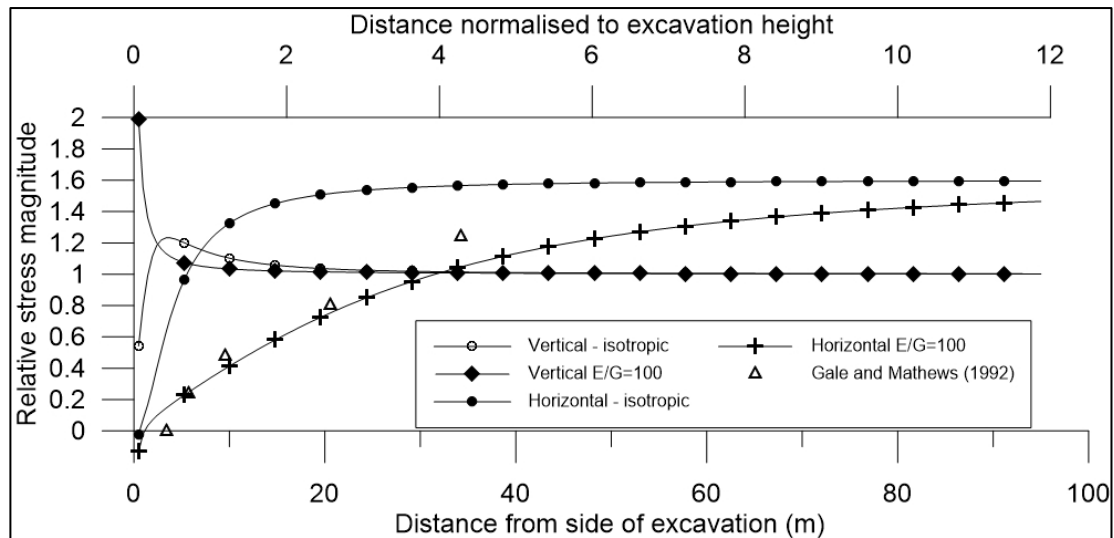


Figure 1: Vertical and horizontal stress around a 5.2 m wide roadway with a 5.0 m softened roof ($K=1.6$).

In Gale (2013), modifications in the horizontal stress field about 10 m above the mining horizon extended at least 50 m – 100 m ahead of the faceline (Figure 2). The same work presents data on the relative magnitude of the induced to pre-mining major principal horizontal stresses as a function of the angle between the pre-mining principal stress direction and the retreat direction. The published data does not include information on the orientation of the induced stresses or the magnitudes of the minor horizontal stresses so it is not possible to resolve the stresses to those acting across a roadway.

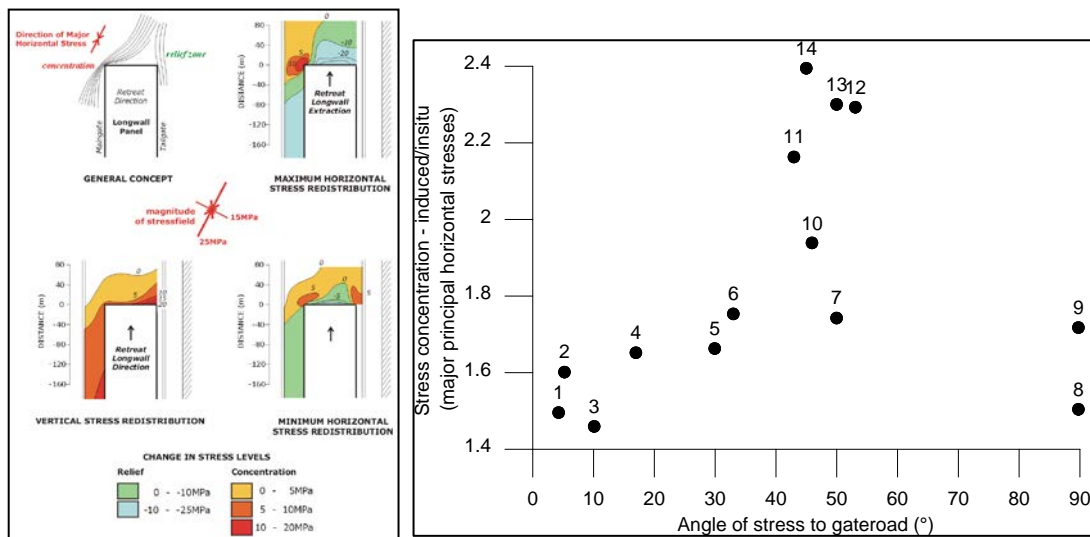


Figure 2: Stress concentration about longwalls (from Gale, 2013).

Gale (2013) considered the three-dimensional stress redistributions about longwall panels which were modelled as voids with heights of 200 m; the report references only isotropic elastic parameters and inspection of the included figures suggest that isotropy was indeed assumed in as much as significant stress changes were only recorded within about 30 m of the goaf zone. It is noteworthy that the modelled concentration factors in Figure 3 are less than those that have been measured (Figure 3). There was negligible concentration of horizontal stresses at 75 m distance or at a distance/void height aspect ratio of 0.375 (red lines in Figure 3).

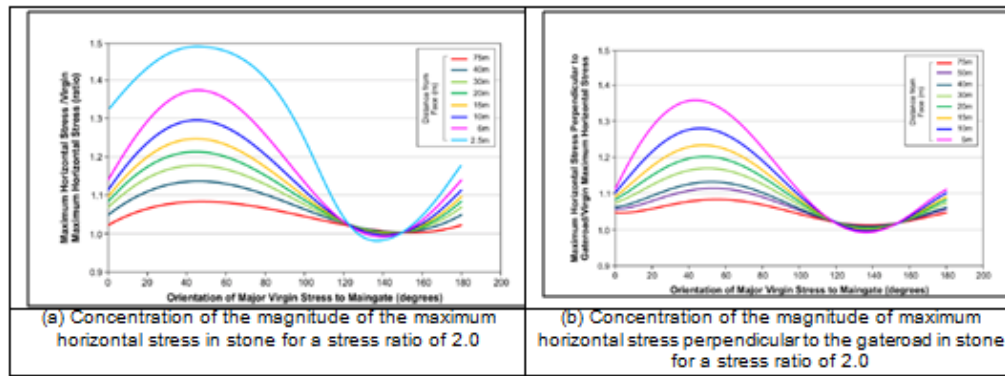


Figure 3: Concentration of horizontal stresses near the gate face corner from Gale (2013)

In discussing interaction between workings Galvin (2016) used an isotropic model with the longwall goaf modelled as a 150 m high soft inclusion with no ability to transmit horizontal stress (effectively a void) and with a rigid floor and found that stress changes were contained within about 30 m of the excavation. In a numerical study Suchowerska et al (2013) examined the role of transverse isotropy in modifying the vertical stresses under coal mine pillars with E/G values of 2.5 to 25 and found that the peak vertical stress increased by 42% over this range; no validation data was provided.

MODEL

Longwall extraction void

In this work an isolated longwall goaf is modelled as a 250 m wide, 1000 m long void (Figure 4) and the height of the void is taken as 100 m based on the empirical models for the prediction of the height of the combined caved and fractured zone assuming a 3 m coal seam (Bai and Kendorski, 1995). A caving angle of 70° has been adopted. Based on reports of fracturing in the floor inducing gas inflows from underlying seams, a 40 m thickness of floor failure is included in the modelled void with an examination of this assumption conducted by considering 0 m and 10 m of floor failure.

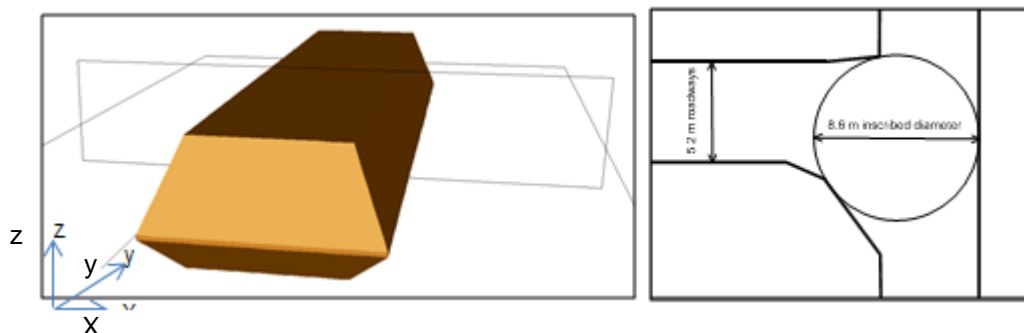


Figure 4: Modelled shape for longwall void and intersection

The rock mass is modelled as a single Transversely Isotropic (TI) material with a Young's Modulus/Independent shear modulus ratio (E/G) of 100 and a Poisson's ratio of 0.2. Isotropic material is also modelled for comparison purposes. The adopted stress regime is major horizontal:minor horizontal:vertical in the ratios of 2:1.5:1.0. In the model the x axis is aligned parallel to the faceline (= direction across the gateroad), the y axis is the direction of face retreat, and the z axis is vertical. Orientation of the stress field with respect to the y axis varied between 0° and 180°. Two and three dimensional codes (Examine2D and RS3) were used; both can be applied in a vertical section at mid-panel but only RS3 can be used for the horizontal section and at the panel ends. Results are presented for the horizontal stress acting across the roadway (σ_{xx}), horizontal stress parallel to the roadway (σ_{yy}), the vertical

stress (σ_{zz}), the ratio of σ_{xx}/σ_{zz} (referred to as the K ratio), and the ratio of the in-plane major principal horizontal stress to the initial vertical stress.

INTERSECTIONS

The geometry of a three-way intersection is shown in Figure 5 and includes 5.2 m wide roadways and an 8.6 m diameter circle in the intersection: the intersection was modelled with a 3 m mining height. The codes RS3 and Examine3D were applied. In the model the major principal horizontal stress is aligned parallel to the through-going roadway. The purpose of these analyses was to examine the increase in the height of failure above an intersection so that plane-strain analyses of roadways can be extrapolated to the more complex three-dimensional case of an intersection. As will be discussed, the visualisation of the RS3 results were impacted to some degree by the meshing. In RS3 a friction angle of 50° was used in combination with the E/G ratio of 100 (Seedsman 2017). For Examine3D to compensate to some degree for the inability to invoke transverse isotropy a friction angle of 35° was selected to give a similar failure height as the RS3 analysis.

RESULTS

Mid panel

Figure 5 presents results for the concentration of the vertical stress and the change in the ratio of the horizontal to vertical stress along a mid-panel vertical section. The width of the zone of increased vertical stress is less for the TI assumption (<75 m) compared to the isotropic (250 m). The TI assumption gives a wider zone for the reduction in horizontal stress compared to the isotropic. The K ratio for the isotropic assumption approaches far-field value of 1.5 at about 300 m offset whereas at the same distance the K ratio for the TI material is 0.77 (Examine2D) or 0.99 (RS3). In fact the far field stress conditions are not attained within the 800 m that have been modelled for the TI assumption.

The mining significance of this result is that isotropic models substantially underestimate the extent of horizontal stress relief provided by a longwall goaf. Isotropic models would suggest that the driveage for the next panel would be in a stress field similar to the pre-mining condition, whereas the horizontal stress could be about half the pre-mining levels. It is noted that there are negligible differences in the prediction of the vertical stress levels for the driveage in the next panel.

Floor failure

Figure 6a presents the results of 2D analyses with three different floor void thicknesses. The extent of floor failure has a major influence on the pattern for the TI material but less of an influence for the isotropic material. Once again the TI material returns a wider zone of impact for the 10 m and 40 m floor voids. For the isotropic assumption and the TI assumption with no floor void the change in the K ratio is confined to a width less than about 200 m.

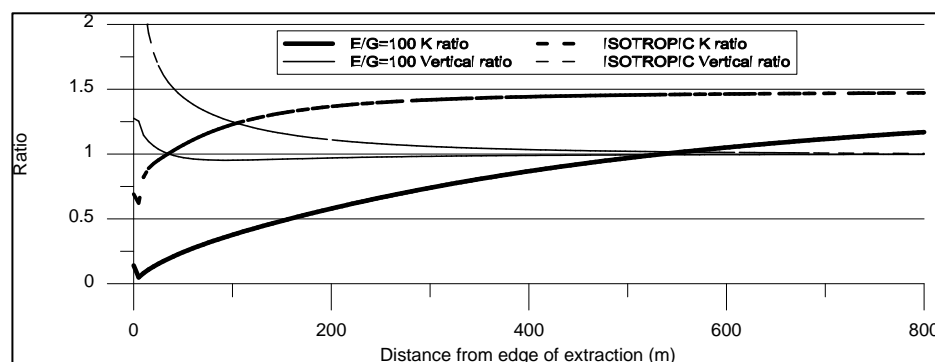


Figure 5: Comparison of isotropic and transversely isotropic assumptions for a vertical section at mid-panel (Examine2D model)Figure 6b shows the sensitivity of

the K ratio developed at 400 m offset from the longwall void to the height above and below the mining level for two values of the floor void thickness. There are negligible differences if the floor is considered rigid or if the rock mass is considered isotropic. The combination of transverse isotropy and floor void thickness results in substantial variations – a 0.1 change in the K ratio for a 10 m change in vertical location.

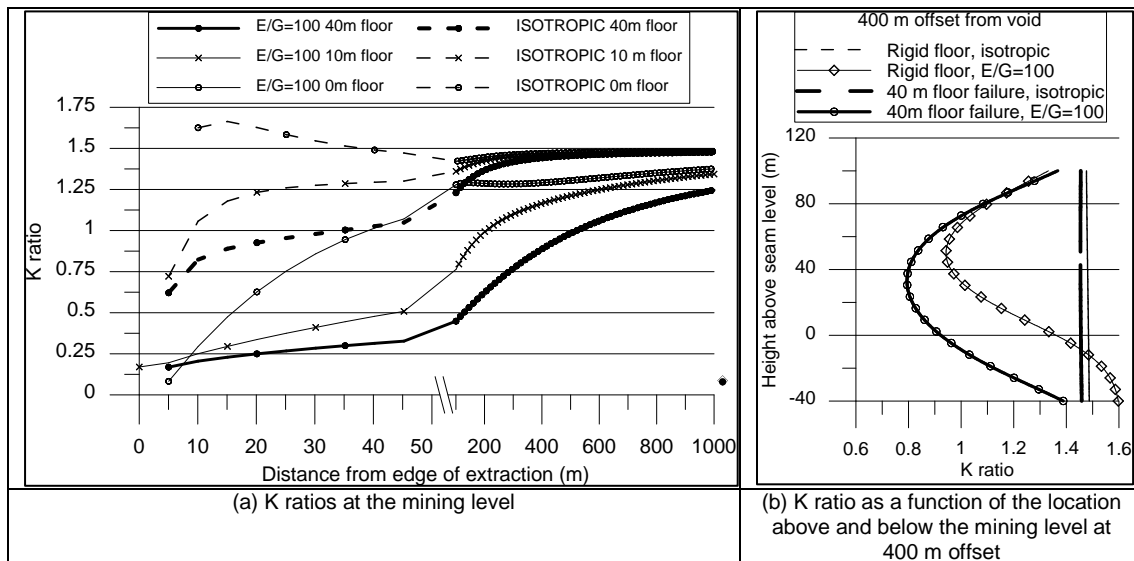


Figure 6: Influence of the floor failure zone on the K ratio for a section normal to the longwall void located at mid-panel

The mining significance of this result is that there may be a substantial stress reduction in the travel road behind the longwall face. These may not be sufficient to induce tensile failure but the stress reduction may result in loosening or collapse of the immediate roof if it had undergone failure at the maingate corner.

Maingate corner

Analyses for the maingate corner utilised RS3. Figure 7 presents data in terms of the resolved stresses and the in-plane major principal stress for the case of the longwall retreating parallel to the major principal horizontal stress. The figure shows a rotation of the direction of the major stress with a concentration similar to that reported attained about 20 m from the face line (about 1.6 in Figure 2). Changes in the magnitude of the horizontal stresses extend out about 150 m and there are some rotational impacts out to 300 m and beyond.

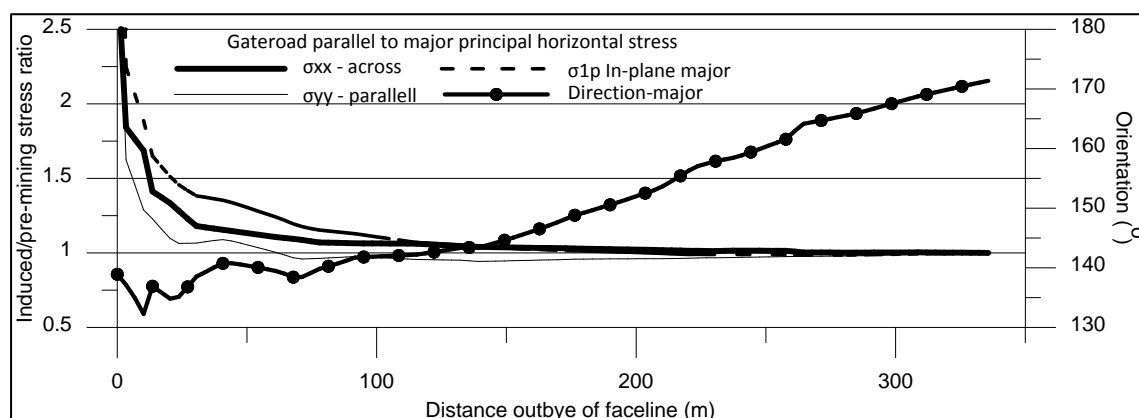


Figure 7: Details of horizontal stress components for the TI assumption and the roadway parallel to the major principal horizontal stress

Resolved stresses

Figure 8 compares the TI and isotropic assumptions and while the patterns are somewhat similar the magnitudes of the changes are substantially different. For example the modelled vertical stress at the faceline is 2.1 times the pre-mining value for the TI case compared to 1.55 for the isotropic case. The concentration of the σ_{xx} horizontal stress at the faceline is also greater at 2.75 compared to 1.75. An important observation is that close to the faceline the K ratio decreases as a result of a greater concentration of the vertical stress compared to the horizontal stress.

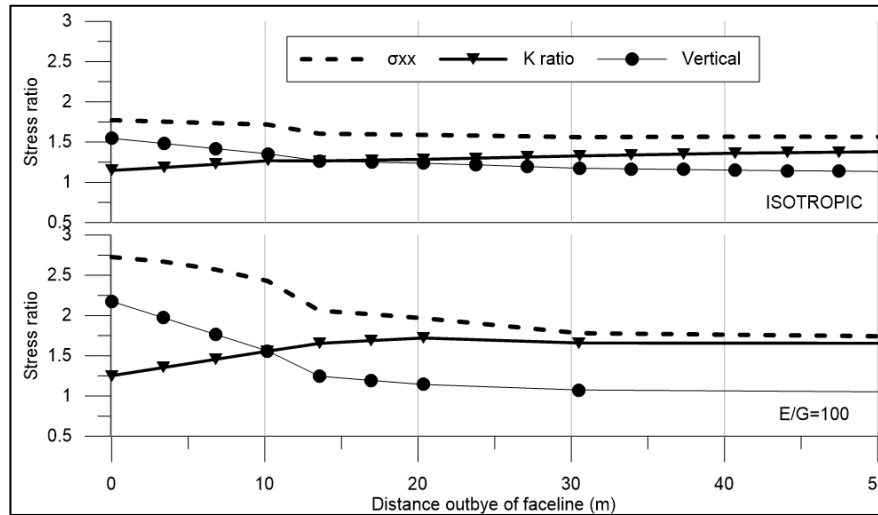


Figure 8: Horizontal and vertical stress acting in the belt road (20° orientation to the major principal horizontal stress)

The concentration of the magnitude of σ_{xx} compared to the pre-mining value as a function of the orientation of the roadway with respect to the direction major principal horizontal stress (Figure 9) for the TI case is much greater than that reported by Gale (2013) as presented in Figure 3b. As expected the concentration levels are greater for the TI case and are somewhat similar to the measured data in Figure 2 if the frame of reference is taken at about 12 m from the face line. The mining significance of this result is that the measured stress concentrations are better explained by a transversely isotropic model compared with an isotropic model.

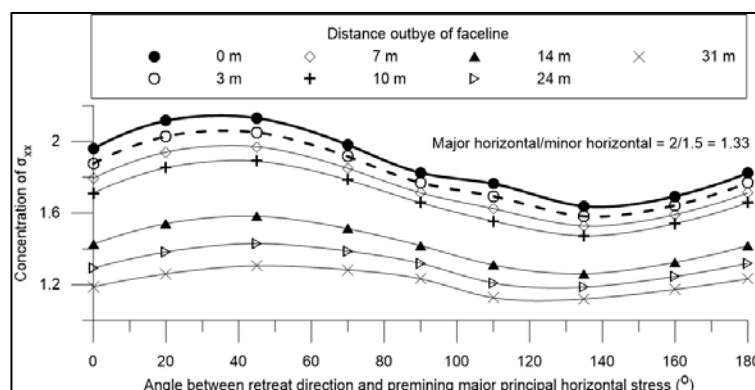


Figure 9: Concentration of σ_{xx} as a function of the retreat direction and distance from the face line

Stress shadows

Figure 10 shows the relative magnitude of the σ_{xx} stresses developed on a horizontal plane at the seam level when the direction of longwall retreat is 20° from the direction of the major horizontal stress: the approximate location for a K ratio of 1.0 highlighted with white dashes.

In Figure 11 the in-plane stresses are shown for a line located at the mining level and 250 m offset from the longwall. There are significant reductions in σ_{xx} to a K ratio of about 1.0 inside of about 250 m from each end of the void. There are minor variations in σ_{yy} .

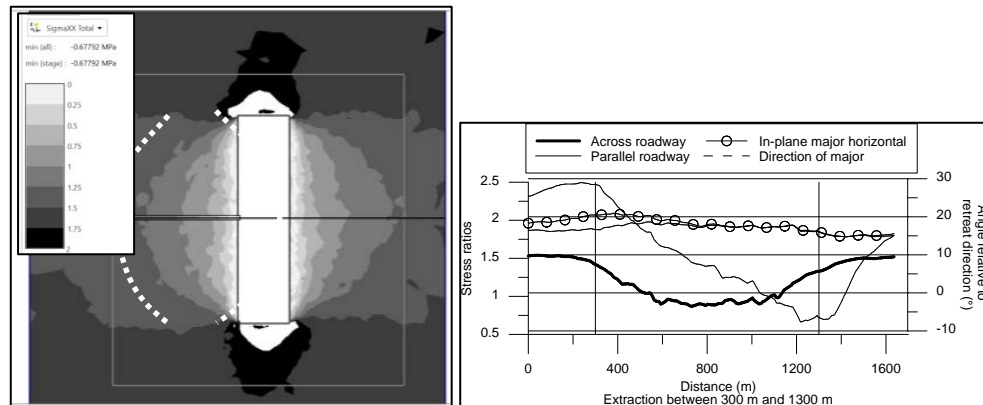


Figure 10: (a) Relative magnitude of horizontal stress acting across the gateroads (σ_{xx}) for an alignment of 20°, (b) section drawn at 250 m off set.

The significance of this result is that when a longwall face is located adjacent to a previous goaf there will be lower horizontal stress magnitudes at the face/gate corner so long as the face/gate corner is inside a line drawn at about 45° from the previous panel ends. Perhaps it would be better to refer to a stress shadow beside a longwall instead of a stress notch at the ends.

Intersections

The isosurfaces for a strength factor of 1.0 (Figure 11) show an increase in the height of failure above an intersection compared to the roadway. The ratios of the failure heights are similar to the ratio of the inscribed diameter to the roadway width (Table 1) .

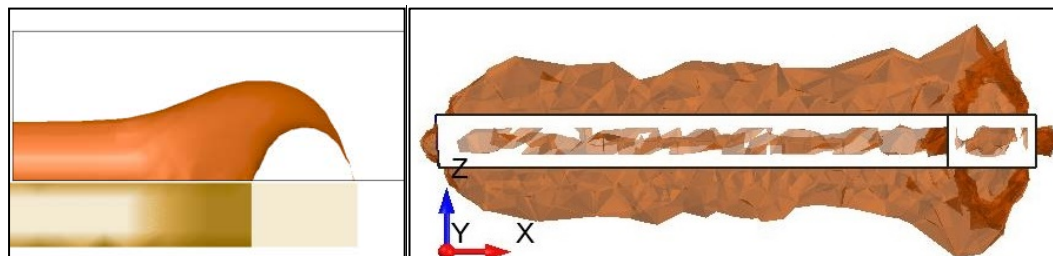


Figure 11: Examine3D and RS3 models showing failure heights above intersections

Table 1: Height of failure above roadways and intersections

| | Roadway (m) | Intersection (m) | Ratio |
|----------------|-------------|------------------|-------|
| Examine3D | 2.8 | 4.74 | 1.66 |
| RS3 | 3 | 5.04 | 1.68 |
| Diameter ratio | | | 1.65 |

The significance of this result is that a correction factor based on the ratio of the diameter of inscribed circles can be used to extend plane strain (2D) models of failure heights above headings to failure heights above intersections.

DISCUSSION

This paper has shown how substantially different understandings of the stress fields around longwalls may be obtained depending on the selection of input parameters to simple

numerical models. Using a ratio of the Young's modulus to Independent Shear Modulus of 100 provides a good match to measured stress relief around roadways and extending this parameter to a longwall goaf indicates the possibility of substantial stress changes extending almost 1 km.

Applicability of the E/G ratio

Brady and Brown (1985) provide an equation to estimate the independent shear modulus for a rock mass with a single set of parallel joints (bedding) which requires an estimate of the joint shear stiffness. Bandis et al (1983) published an empirically-derived relationship that involves the normal stress, the basic friction angle, the Joint Roughness Coefficient, the Joint Compressive Strength (equal to UCS for a clean joint), and the length of the joint. Referring to Figure 12, an E/G ratio of 100 is consistent with an average bedding spacing of 150 mm for mining depths of 400 m to 500 m. It may be possible to use this relationship to estimate alternative E/G ratios for different bedding thicknesses and hence to extend the analyses outlined in this paper to more thickly bedded units.

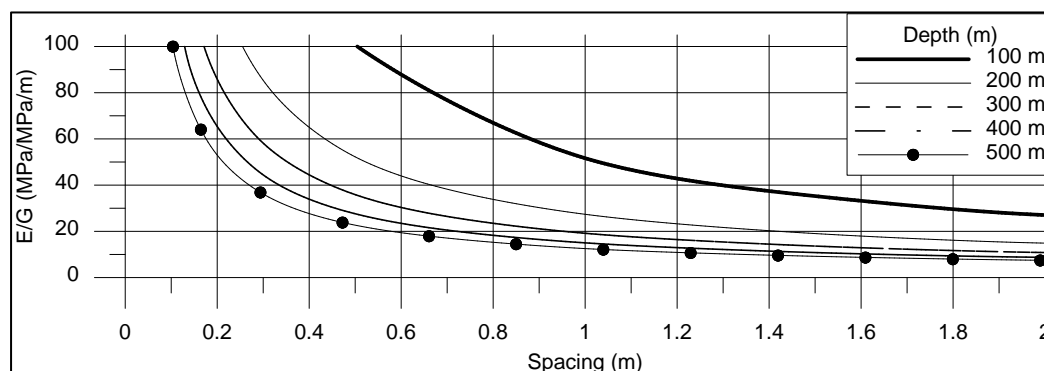


Figure 12: Variation in the E/G ratio as a function of bedding spacing ($\phi_r=30^\circ$, JRC=1, JCS=UCS=60 MPa, L= 0.5 m, modular ratio=250)

Mining induced changes to the virgin stress field

Based on this work it is suggested that only the first panel in a new mining area, or when subsequent panels are longer, will the gateroads be exposed to the virgin stress field. This means that contiguous longwalls operate in a much reduced horizontal stress environment except near the start or end lines of the previous longwall. The first longwall panel in a new mining district may be exposed to higher horizontal stresses even if the depths of cover and the structural geology are similar. There are a number of implications to this. Firstly, the design and interpretation of stress measurement programs need to consider the distance from existing longwall extraction. Secondly, the stress footprint of a longwall may be much wider than previously considered and this may need to be considered when considering so-called far-field subsidence movements.

Brittle failure near the maingate corner

The presentation of the data in terms of the K ratio and the relative change in the vertical stress allows ready integration with the TIB brittle failure criterion (Seedsman, 2017). The rock strength index (RSI) can be calculated from the Unconfined Compressive Strength (UCS) and the vertical stress estimated from the depth of cover and the vertical stress: $RSI = UCS / (Depth \times \text{average overburden density})$ so that for a UCS of 50 MPa, a mining depth of 350 m and a density of 2500 kg/m³ the pre-mining RSI is 5.7.

Figure 13 presents the stress path for an isolated longwall panel in a stress field with principal stresses in the ratio of major horizontal:minor horizontal:vertical stress of 2:1.5:1. Three stress paths are indicated – parallel, 45° and normal to the major principal horizontal stress. As discussed above the impact of the longwall extraction begins about 300 m distant and the vertical stress starts to increase at about 100 m distant. The stress condition associated with

the greatest height of TIB failure develops about 24 m from the faceline and the failure heights for the maingate are 5.0 m, 6.6 m and 8.2 m for the three respective orientations and hence 8.3 m, 11 m and 13.5 m for the intersections.

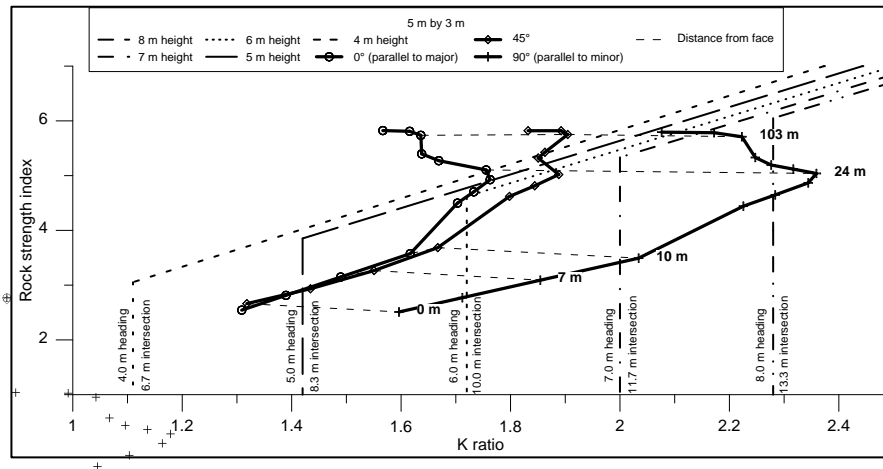


Figure 13: Longwall stress paths projected onto TIB design chart (bold numbers + indicate distance from faceline, diagonal and vertical lines are heights of brittle failure)

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